



# Development and Performance Evaluation of Optical Sensors for High Temperature Engine Applications

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## **Abstract**

This paper discusses fiber optic sensors designed and constructed to withstand extreme temperatures of aircraft engine. The paper describes development and performance evaluation of fiber optic Bragg grating based sensors. It also describes the design and presents test results of packaged sensors subjected to temperatures up to 1000 °C for prolonged periods of time.

## **Introduction**

The major obstacle that stops introduction of fiber optic sensor technology into engine flight control and health monitoring has been the inability of the sensors to withstand high temperatures. At high temperatures the optical fibers experience devitrification and a loss of transmissivity (Refs. 1 to 3). In addition, conventional optical sensors based on fiber Bragg gratings (FBGs) experience diffusion of dopants. The diffusion of dopants results in the dissipation of gratings themselves (Ref. 4). The temperature affecting performance of the silicon based fiber optic sensors varies and depends on the type and concentration levels of dopants. However, the recent developments have shown that some FBGs could operate in extreme thermal environments (Refs. 5 to 8).

This paper discusses optical FBG based sensors packaged to operate at temperatures up to 1000 °C. FBGs are gratings written holographically in the core of optical fiber along its optical axis using ultraviolet radiation. Prior to exposure to radiation the fiber is doped with germanium dioxide or germania. It has been shown that the presence of the dopant causes the otherwise homogeneous glass to change its properties in the regions exposed to the radiation. The process is widely used in the communication industry to construct wavelength filters and routers that employ Bragg gratings.

## **Sensor Design and Construction**

The process of manufacturing a high temperature FBG sensor consists of two steps. The first step is to provide a sturdy packaging that would permit an easy handling of the device. At this step, FBGs used to construct sensors are placed inside housings that consist of one or several tubes placed inside each other concentrically and made out of high temperature ceramic. One of the ceramic tubes has an inner diameter that is small but sufficient to accommodate the fiber and provides protection to the fiber surface. The fiber with the FBG is placed in such a way that the FBG is located inside the small diameter tube close to one of its ends. A fiber optic connector is attached to another end of the sensor housing. After completion of this step, the probe is packaged with an FBG inside and connectorized. An example of such a packaged probe is shown in Figure 1.

The second step in the manufacturing process involves an exposure of the packaged probes to 1000 °C temperatures. The apparatus built and used during the manufacturing and testing of the sensors is shown in Figure 2. The setup can accommodate simultaneously up to 4 probes (sensors) that are inserted inside the furnace through special ports. The probes are exposed to high temperatures. The FBGs placed inside the furnace return optical signals with information about the temperature inside the furnace. That information is encoded in the wavelength of the optical signal. The wavelength information is analyzed and decoded with the optical spectrum analyzer. From the spectrum analyzer the information is sent to a computer for further analysis. The computer is equipped with the LabVIEW (National Instruments) software that controls individual pieces of hardware, collects and process the data.

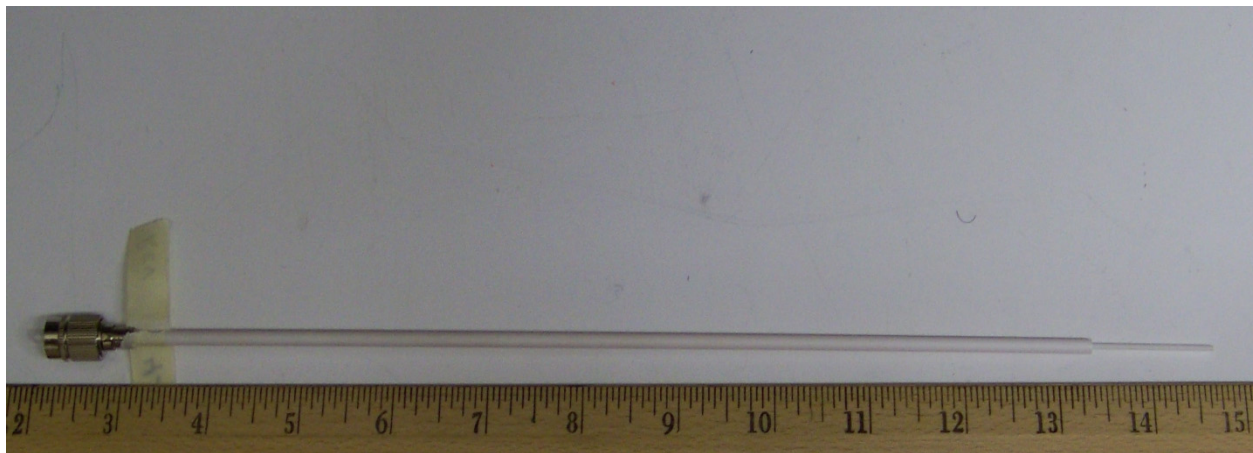


Figure 1.—A probe packaged and connectorized with an FBG inside.

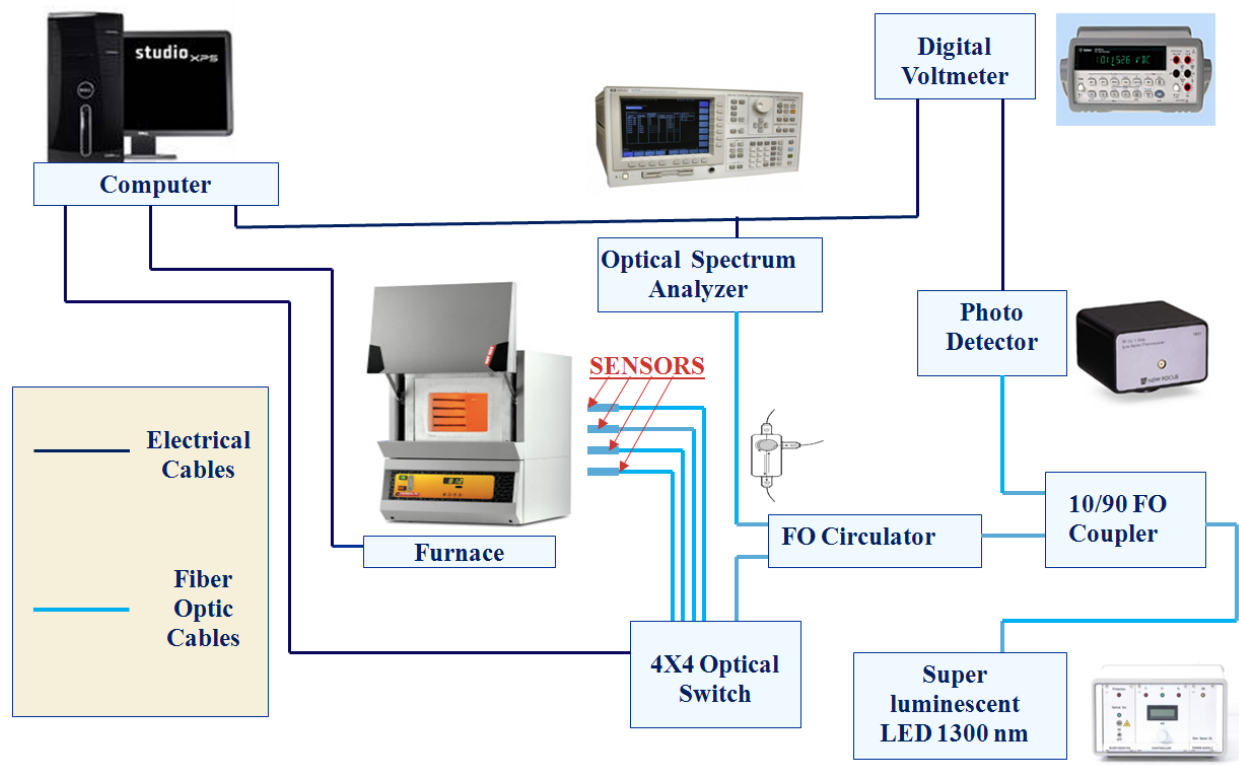


Figure 2.—Schematic diagram of a setup to manufacture and test high temperature optical sensors.

It has been shown that the exposure of conventional FBGs to extreme temperatures leads to formation of thermally stable gratings (Refs. 5 and 6). Those secondary gratings appear in place of the original Bragg gratings written in the GeO<sub>2</sub> doped silica fibers by exposing the fibers to UV light. The time needed for the formation of secondary gratings varies and depends mostly on the heating rate. After completion of the second step of the manufacturing process the packaged probe becomes a high temperature fiber optic sensor.

## Performance Evaluation of High Temperature FBG Sensors

Data were recorded from tests performed on several packaged high temperature sensors constructed following the steps described in the previous section. In the process of construction, the packaged sensors with the original FBG were heated slowly to 1000 °C and kept at that temperature for various periods of time. The sensors were also exposed to thermal cycling at different heating rates. Tables 1, 2, and 3 sum up the thermal conditions the sensors were subjected to.

TABLE 1.—CONTINUOUS EXPOSURE

[Total, Hours]

Sample no.	Sensor no.	800 °C	1000 °C
A1	1246-71716	200	560
A2	1246-71719	40	1100
A3	1246-71724	200	610
A4	1246-71729	200	560
A5	1246-71730	--	50
A6	1246-71734	80	150
A7	1246-71735	80	100
B1	1618-1-9	40	15
B2	1618-1-10	40	15
B3	1618-1-11	--	15

TABLE 2.—THERMAL CYCLING

[Number of cycles]

Sample no.	Sensor no.	RT-1000 °C	400 to 800 °C
A1	1246-71716	20	100
A2	1246-71719	--	20
A3	1246-71724	20	100
A4	1246-71729	20	100
A5	1246-71730	--	--
A6	1246-71734	--	20
A7	1246-71735	--	20
B1	1618-1-9	--	20
B2	1618-1-10	--	--
B3	1618-1-11	--	--

TABLE 3.—THERMAL CYCLING

[Heating rates and time at maximum temperature, hours.]

Heating rates and time at maximum temperature, hours.										
Sample no.	Sensor no.	RT-1000 °C		400 to 800 °C						
		Rates, C/min	Hold	Rates, C/min						Hold
A1	1246-71716	2	3 h	0.5	2	--	6	8	10	2 h
A2	1246-71719	--	--	--	--	5	--	--	--	2 h
A3	1246-71724	2	3 h	0.5	2	--	6	8	10	2 h
A4	1246-71729	2	3 h	0.5	2	--	6	8	10	2 h
A5	1246-71730	--	--	--	--	--	--	--	--	--
A6	1246-71734	--	--	--	2	--	--	--	--	2 h
A7	1246-71735	--	--	--	2	--	--	--	--	2 h
B1	1618-1-9	--	--	--	--	5	--	--	--	2 h
B2	1618-1-10	--	--	--	--	5	--	--	--	2 h
B3	1618-1-11	--	--	--	--	--	--	--	--	--

## Results and Conclusions

A process of manufacturing high temperature FBG-based sensors has been developed and demonstrated. The process has permitted construction of robust packaged sensing devices capable to withstand extreme temperatures. The process starts with a construction of ceramic housings for polyimide coated fiber with an FBG. The structures then are placed into a furnace and heated slowly from room temperature to 1000 °C. After reaching 1000 °C the sensors are kept at that temperature for periods of time from 20 to 50 hr and then are allowed to cool back down the room temperature. The entire process is controlled and recorded using LabVIEW software. Data obtained during the manufacturing process is shown in Figures 3 and 4. Figure 3 depicts typical temperature (time) dependent intensity changes in the signal reflected back by the grating. In the case shown in Figure 3 the heating rate is 2 °C/min. Thus, the temperature of 1000 °C is reached in about 8 hr from the start of the process. The plot is similar to the one obtained in the previous work (Ref. 6) for a free standing fiber and also displays a hump in the normalized peak power profile. The hump is associated with the formation of the secondary thermally stable grating.

Figure 4 shows typical changes in the wavelength during the heating and cooling process. The lower and upper lines represent changes in the wavelength correspondingly during the heating and cooling process.

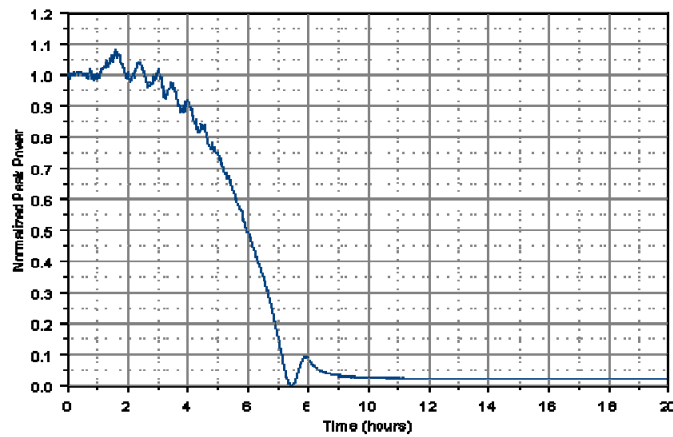


Figure 3.—Change in the relative intensity during the first 20 hr of the manufacturing process.

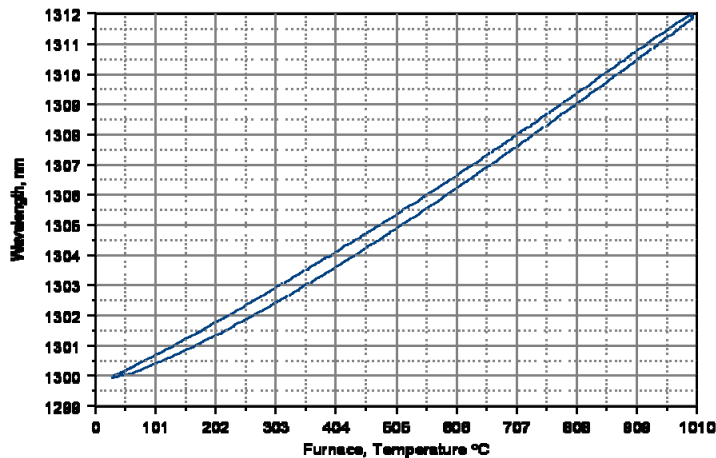


Figure 4.—Wavelength dependence on the furnace temperature during the manufacturing heating and cooling process.



After the manufacturing process is completed the sensor is subjected to a continuous exposure to high temperature. Figure 5 shows the wavelength stability of a typical sensor over a 500 hr long exposure at 1000 °C.

The evaluation of the sensor's stability displayed in Figure 5 has shown that the 1000 °C temperature corresponds to an approximate wavelength reading of 1311.8 nm. Over the period of 500 hr, while the temperature is maintained at a 1000 °C level, the wavelength drifts between approximately 1311.95 and 1311.65 nm with a maximum deviation of  $\pm 0.15$  nm. A straight line on the left side represents the peak wavelength during the initial heating of the sensor from the room temperature to 1000 °C.

Another set of tests of a manufactured sensor involves a thermal cycling. The sensor is subjected to 20 thermal cycles from 400 to 800 °C with various heating rates. Figures 6 and 7 show typical responses of a sensor to the thermal cycling. In Figure 6 the plot follows wavelength readings in time domain as the sensor undergoes 20 cycles from 400 to 800 °C with 2 hr long holds at 800 °C. Figure 7 tracks wavelength readings as a function of temperature during the thermal cycling.

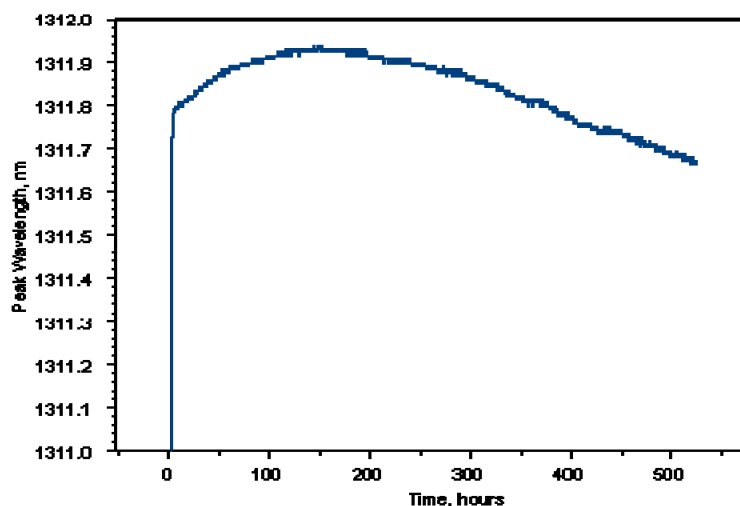


Figure 5.—Wavelength stability of a sensor exposed to 1000 °C for 500 hr.

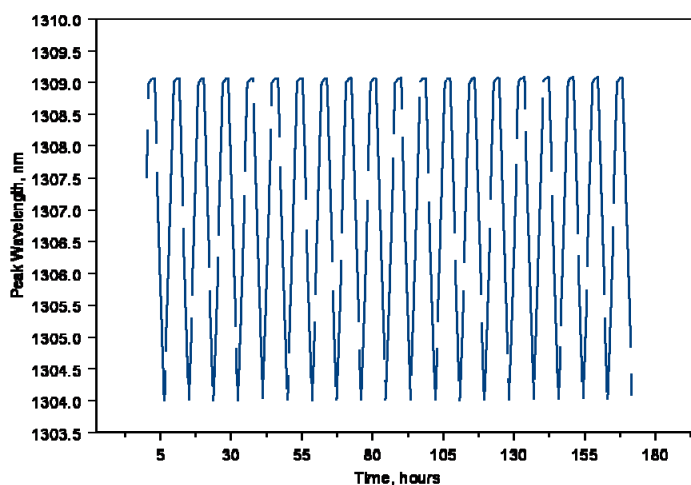


Figure 6.—Wavelength readings during 20 thermal cycles from 400 to 800 °C.

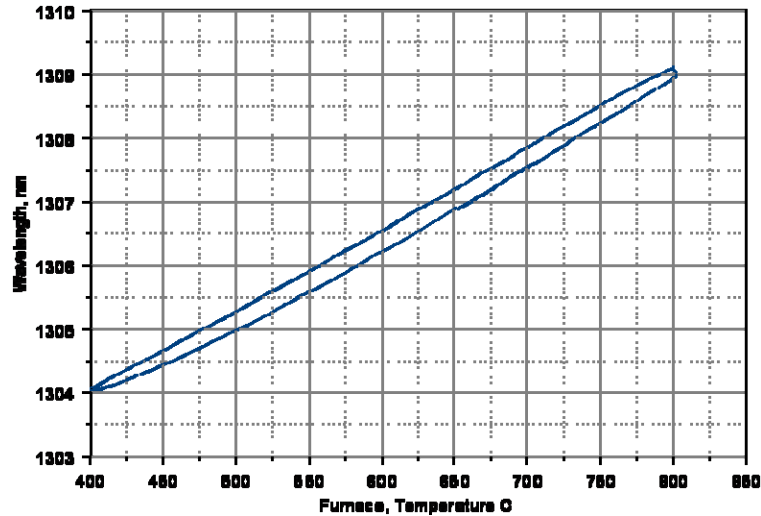


Figure 7.—Wavelength readings as a function of temperature during thermal cycling from 400 to 800 °C.

Similarly to the plot in Figure 4, the lower and upper lines in Figure 7 represent correspondingly the heating and cooling periods of the thermal cycling.

More vigorous durability tests are currently being performed.

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